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Differential and STXS cross section measurements at CMS, combination and EFT interpretation

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The CMS Collaboration summarizes the results from combined measurements and interpretations of Higgs boson production and decay rates, utilizing the full LHC Run 2 dataset corresponding to 138 fb^{-1} of $\sqrt{s}$ = 13 TeV proton-proton collisions. Results are based on the combination of distinct decay channels, characterizing the Higgs boson through signal-strength modifiers, fiducial and differential production cross sections, and for the first time by measuring kinematic regions defined by the Simplified Template Cross Section (STXS) framework. Furthermore, these results are interpreted within Standard Model Effective Field Theory (EFT) frameworks to probe potential Beyond the Standard Model physics. Highlights from early Run 3 data and projections for the High-Luminosity LHC era are also discussed.

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1. Introduction

The discovery of the Higgs boson by the ATLAS and CMS Collaborations in 2012 [1, 2] initiated a research program aimed at characterizing its properties with high precision. The data collected during Run 2 of the LHC has enabled significant progress in testing the Standard Model (SM). These precise measurements also enable the search for possible deviations from SM predictions, which could indicate interactions from new physics.

2. Combined Measurements and Interpretations of Higgs Boson Production and Decay Rates at $\sqrt{s} = 13$ TeV

The comprehensive study [3] undertaken by the CMS Collaboration with the full LHC Run 2 data of 138 fb^{-1} aims to characterize the Higgs boson and perform the most precision tests of the SM up-to-date. The statistical combination incorporates analyses covering multiple production modes: **ggH**, **VBF**, **VH**, **$\mathbf{t\bar{t}H}$**, **tH** and following Higgs boson decay channels: $\mathbf{H \to \gamma\gamma}$, $\mathbf{H \to ZZ}$, $\mathbf{H \to WW}$, $\mathbf{H \to \tau\tau}$, $\mathbf{H \to b\bar{b}}$, $\mathbf{H \to \mu\mu}$, and $\mathbf{H \to Z\gamma}$. In addition, the combination incorporates searches for invisible Higgs boson decays (H $\to$ inv) to constrain potential beyond-the-Standard Model (BSM) contributions. An analysis of off-shell Higgs production (H $\to$ ZZ $\to$ 4l) is also included for the first time, providing a direct data-driven constraint on the Higgs boson's total decay width.

The statistical model underlying this combination is a complex global likelihood function, comprising up to about 2,000 distinct event categories and more than 10,000 fit parameters. These parameters include the physical parameters of interest as well as nuisance parameters that account for all known sources of experimental and theoretical systematic uncertainty. To ensure a coherent combination, the input analyses were meticulously aligned. This involved adopting a common signal model with harmonized theoretical uncertainties for Higgs boson production and decay rates.

2.1 Measurements of Signal-Strengths (μ)

Signal-strength modifiers (μ^{if}) scale the measured signal rate of a process relative to the SM expectation. The overall best-fit inclusive signal yield is measured to be $\mathbf{1.014^{+0.055}_{-0.053}}$ times the SM expectation, assuming a Higgs boson mass of $m_H = 125.38$ GeV. This result shows good compatibility with the SM, with a p-value of $\mathbf{p_{SM} = 0.80}$ as illustrated in Fig. 1 *(left)*. The most granular per-production mode fit simultaneously constrains 31 parameters (μ^{if}). The fit shows a small tension ($\mathbf{p_{SM} = 0.02}$) with the SM hypothesis, driven primarily by excesses in μ^{tH}, μ^{WH}, and μ^{ZH}, which are measured to be about two standard deviations above the SM expectation. The per-decay channel fit shows a better compatibility with the SM ($\mathbf{p_{SM} = 0.33}$), with the largest observed deviations in $\mu^{\tau\tau}$ and $\mu^{Z\gamma}$ parameters, however these are still compatible with the SM expectations within the 95 % CL intervals.

2.2 STXS Production Cross Sections and STXS and Branching Fraction Ratios

The Simplified Template Cross Sections (STXS) framework [4] partitions the Higgs boson production phase space into non-overlapping regions (bins) based on the production mechanism and kinematic properties. This strategy aims to both reduce the theoretical dependence of the

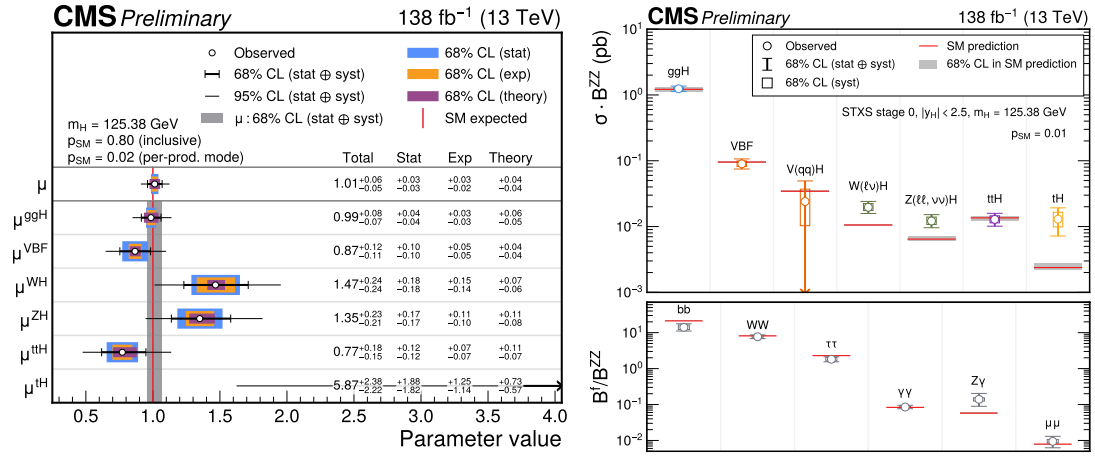

Figure 1: *(left)* **The measured inclusive (μ) and per-production mode (μ_i) signal-strength modifiers**. The 68% CL intervals are decomposed into theoretical systematic (purple), experimental systematic (orange), and statistical (blue) components. The plot indicates the compatibility p-values ($\mathbf{p_{SM} = 0.80}$ inclusive, $\mathbf{p_{SM} = 0.02}$ per-production mode). *(right)* **The measured STXS Stage 0 cross sections ($\sigma_i \times B_{ZZ}$) and branching fraction ratios ($R_{f/ZZ}$)**. The measured quantities (points/lines) are compared to the SM prediction (red line) and its theoretical uncertainty (grey band). The overall compatibility is $\mathbf{p_{SM} = 0.01}$. [3]

measurement and isolate regions particularly sensitive to BSM physics. The combined STXS measurements from the CMS experiment [3] are presented in two approaches.

Cross sections are measured at the production mode level (STXS Stage 0) multiplied by the $\mathbf{H \to ZZ}$ branching fraction ($\sigma_i \times B_{ZZ}$). Modifications in other branching fractions are incorporated by floating the ratio $R_{f/ZZ} = B_f/B_{ZZ}$. In this formalism, theory normalization uncertainties are excluded from the fit and attributed instead as uncertainty on the SM prediction. Fig. 1*(right)* shows measured STXS Stage 0 cross sections and branching fraction ratios. The overall compatibility is measured to be $\mathbf{p_{SM} = 0.01}$, driven by deviations in σ_{tH} and the branching fraction ratios $R_{b\bar{b}/ZZ}$ and $R_{Z\gamma/ZZ}$.

The STXS Stage 1.2 is the first combined measurement from CMS, simultaneously fitting **32** STXS pre-defined kinematical (e.g.: on transverse momentum or mass invariant) template bins per production mode. At this high level of kinematic splitting, the statistical uncertainty dominates for all parameters.

The results in Fig. 2 show noticeable deviations, particularly in the high p_T^V leptonic VH regions. The **WH** lep $p_T^V > 250$ GeV and **ZH** lep $p_T^V > 250$ GeV regions are measured to be at least two standard deviations above the respective SM predictions. Between **4** ratios of branching fraction measurements, a noticeable tension is present for $R_{b\bar{b}/ZZ}$ as for the Stage 0 approach. The overall compatibility with the SM is $\mathbf{p_{SM} = 0.06}$.

2.3 BSM Interpretations

The STXS results are interpreted within the coupling modifier (κ) framework and the SM Effective Field Theory (SMEFT) framework to constrain potential BSM physics. The combined results [3] provide constraints on couplings to vector bosons (κ_W, κ_Z) and fermions (κ_t, κ_b, κ_τ, κ_μ). Fig. 3 *(left)* shows the results of the resolved coupling modifier fit as a function of the mass of

the probed particles. The vector boson coupling modifiers, $\kappa_{\mathbf{W}}$ and $\kappa_{\mathbf{Z}}$, are measured with 68 % CL intervals of 5 % and 6 %, respectively. The coupling modifiers for third generation fermions are equally well constrained with 68 % CL intervals ranging from 5 % for $\kappa_{\mathbf{t}}$ to 12 % for $\kappa_{\mathbf{t}}$. The coupling modifier to muons is measured with a 68 % CL interval of 20 %. These measurements show decent compatibility with the SM hypothesis over three orders of magnitude in particle mass, with an overall p-value of $\mathbf{p_{SM} = 0.12}$.

The effective configuration of the coupling modifier is fitted under three different assumptions about the total Higgs boson decay width. These $\kappa_{\mathbf{j}}$ fit results are summarises in Fig. 3 *(right)*. Results are shown for models assuming no BSM contributions, floating BSM contributions with external constraint $|\kappa_V| \leq 1$ and floating BSM contributions with off-shell inputs. The largest tension is observed for the $\mathbf{H \to Z\gamma}$ decay. The inclusion of off-shell $\mathbf{H \to ZZ \to 4}\ell$ analysis regions allows the Higgs boson total decay width to be constrained directly from data for the first time in CMS. In this model including, the branching fraction to invisible final states $\mathbf{B}_{\text{inv}}$ is constrained to be less than **13**% (95 % CL) by the $\mathbf{H \to inv}$ searches included in this combination. The branching fraction to undetected BSM final states $\mathbf{B}_{\text{undet}}$, which is not directly measured by any of the input measurements, is estimated to be less than **25**% (95% CL). The $\mathbf{B}_{\text{inv}}$ and $\mathbf{B}_{\text{undet}}$ components together make up the total BSM branching fraction of Higgs decays.

In addition, ratios of coupling modifiers ($\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$) are extracted, and constraints on the Higgs boson trilinear self-coupling are provided through the next-to-leading order electroweak corrections to the Higgs boson production and decay rates. Assuming other Higgs boson couplings are predicted in theSM ($\kappa_{\mathbf{F}}$ and $\kappa_{\mathbf{V}}$ are fixed to **1**), the trilinear self-coupling is measured to be $\kappa_\lambda = \mathbf{2.1}^{+\mathbf{4.0}}_{-\mathbf{3.2}}$, relative to the SM prediction.

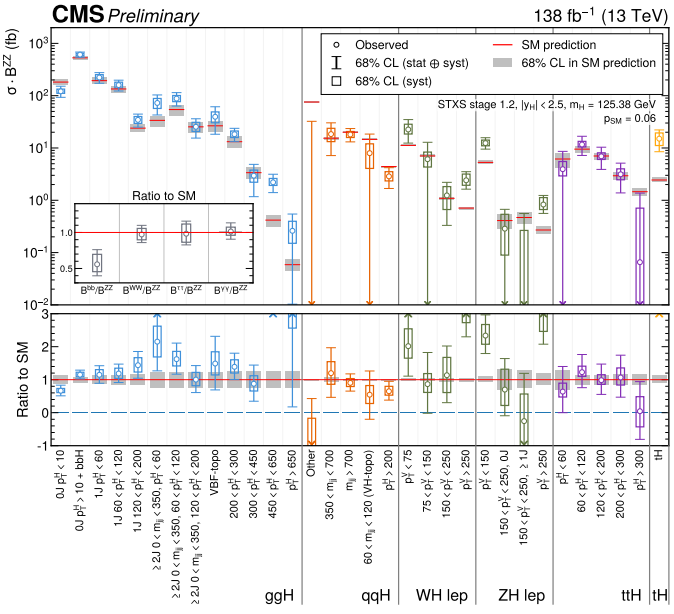

Figure 2: The measured STXS Stage 1.2 cross sections ($\sigma_{\mathbf{i}} \times \mathbf{B_{ZZ}}$) and branching fraction ratios. The ratio panel highlights the measured ratio with respect to SM predictions. Statistical uncertainty dominates due to the high granularity of the measurement. [3]

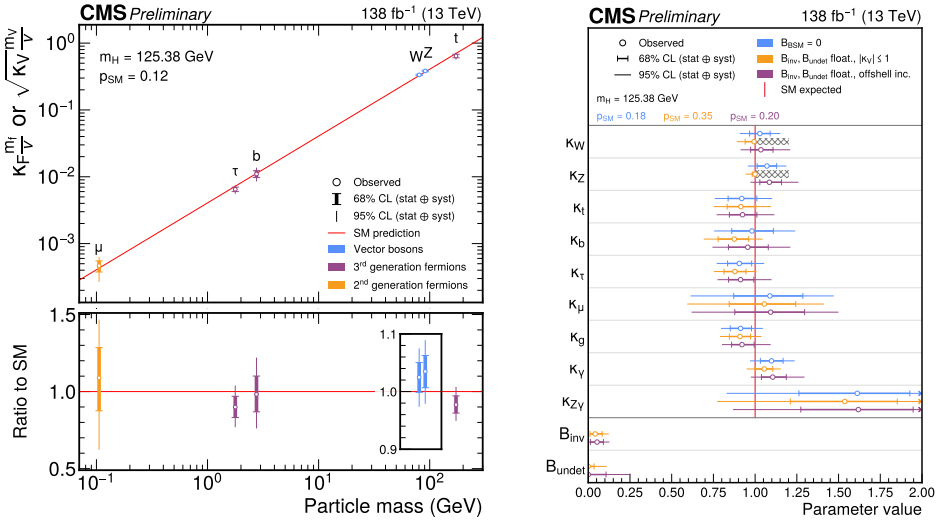

Figure 3: *(left)* **The measured coupling modifiers of the Higgs boson to fermions and gauge bosons, as measured in the resolved coupling modifier fit.** The particle masses are evaluated at the Higgs boson mass scale. The uncertainties in the particle mass values are not shown in the plot. For gauge bosons, the square root of the coupling modifier is plotted to keep a linear proportionality to the mass, as predicted by the SM. *(right)* **The measured Higgs boson coupling modifiers in the effective coupling configuration**. Results are shown for models assuming no BSM contributions (blue), floating BSM contributions with external constraint $|\kappa_V| \leq 1$ (orange, hatched region excluded), and floating BSM contributions with off-shell inputs (purple). [3]

2.4 Measurements using SMEFT and Constraints on Individual Wilson Coefficients

A detailed interpretation in SMEFT framework is also performed by CMS [3]. SMEFT [5] is a Standard Model Effective Field Theory that probe nonresonant new physics effects at a high energy scale Λ without any specific BSM scenario. SMEFT parametrisation of The CMS STXS measurements (Sec. 2.2) is derived using simulation and computed up to quadratic order ($\mathbf{O(c^2/\Lambda^4)}$). Individual constraints are extracted on the SMEFT Wilson coefficients (WC) [6] by scanning one WC while fixing others to zero. In total, the combination is sensitive to **43** of the SMEFT operators. To assess the compatibility of data with the SM, a p-value is computed for each of the WCs. The largest discrepancy from the SM is observed in $\mathbf{c_{Hq}^{(3)}}$ ($\mathbf{p_{SM} = 0.01}$), which is directly linked to the observed excesses in the high $\mathbf{p_V^T}$ leptonic **VH** STXS 1.2 measurements (Sec. 2.2). The tightest constraints are obtained for $\mathbf{c_{HG}}$ and $\mathbf{c_{HB}}$, yielding a 95 % CL lower limit on the new physics energy scale Λ of around **15** TeV.

3. Differential Cross Section Measurements and SMEFT Constraints

CMS performed a model-independent measurement [7] of the Higgs boson differential production cross section in its decay to a pair of W bosons, with a final state that includes two jets and different-flavor dilepton ($e\mu$) with Run 2 data. The production cross sections are measured as a function of the azimuthal angle difference between the two jets presented in Fig. 4 (left). Three different signal extraction configurations are employed to measure the overall Higgs boson cross

section in association with two jets produced through VBF and ggF modes. No significant deviations from the SM were found in any of the differential distributions. Differential cross section measurements are further utilized to constrain Wilson coefficients within the SMEFT. The most stringent constraints are obtained on the Charge Conjugation Parity (CP)-even $\mathbf{c_{HW}}$ (illustrated in in Fig. 4 (right)) coefficient from the VBF cross section measurement, and on the CP-even $\mathbf{c_{HG}}$ coefficient from the ggH cross section measurement.

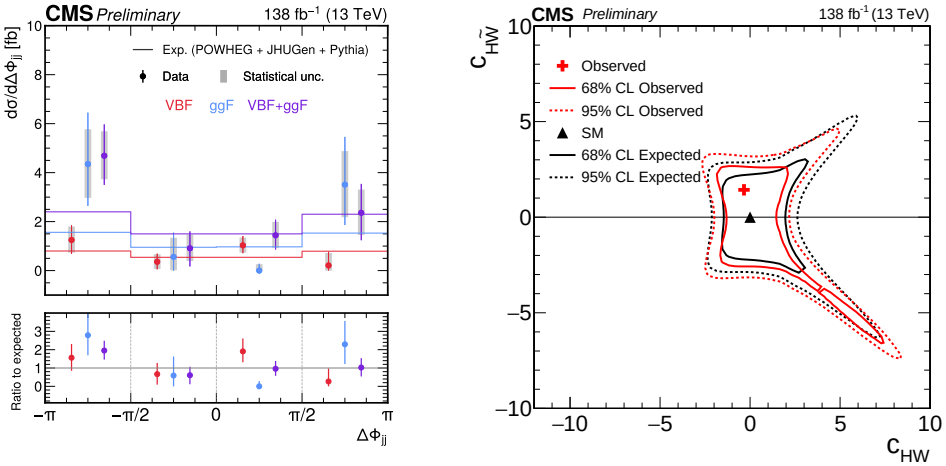

Figure 4: *(left)* **Measured fiducial cross section of the VBF and ggH production processes**. Colored markers represent the extracted cross section values from data, with error bars showing the combined statistical and systematic uncertainties. The lower panel displays the ratio of the measured values to the SM expectation. *(right)* **Two-dimensional expected and observed scans for the pairs of Wilson coefficients $\mathbf{c_{H\tilde{W}}}$ and $\mathbf{c_{HW}}$**. Solid (dotted) lines correspond to the 68 % (95 %) CL contours. [7]

4. Run 3 Early Results ($\sqrt{s}$ = 13.6 TeV)

New measurements using early Run 3 data collected in 2022 ($\sim$ 34.7 fb^{-1}) provide updated fiducial cross sections in clean channels:

- $H \to ZZ \to 4\ell$**:** $\sigma_{\text{fid}} = \mathbf{2.89}^{+\mathbf{0.53}}_{-\mathbf{0.49}}(\text{stat})^{+\mathbf{0.29}}_{-\mathbf{0.21}}(\text{syst})$ fb [8], consistent with the SM expectation of $3.09^{+0.27}_{-0.24}$ fb. Cross sections are measured in a fiducial region closely matching the experimental acceptance, both inclusively and differentially, as a function of the transverse momentum and the absolute value of the rapidity of the four-lepton system.

- $H \to \gamma\gamma$**:** $\sigma_{\text{fid}} = \mathbf{74} \pm \mathbf{11}(\text{stat})^{+\mathbf{5}}_{-\mathbf{4}}(\text{syst})$ fb [9], in agreement with the SM expectation of 67.8 ± 3.8 fb. A new normalizing-flow-based method is applied to correct the imperfect modeling of reconstructed photon variables in the simulation and to reduce the associated systematic uncertainties.

5. HL-LHC Projections ($\sqrt{s}$ = 14 TeV)

The High-Luminosity (HL) LHC physics programme will be crucial for deepening the understanding of fundamental physics, enabling in particular precision studies of the Higgs sector and enhancing sensitivity to rare processes and potential new physics. Projections for the HL-LHC era,

typically assuming the luminosity of 2 ab^{-1} or 3 ab^{-1} under a given systematic scenario, indicate significant improvements in precision. To define scenario S2, it is assumed that experimental systematics scale down with luminosity and theoretical are halved assuming progress in calculations [10]. The projected STXS constraints are shown for $L = 3\ ab^{-1}$ under the S2 scenario in Fig. 5. The 68 % CL intervals in the measurements are reduced significantly compared to the Run 2 constraints as presented in Fig. 2. For many measurements, the sensitivity is comparable to the theoretical uncertainty, opening up the scenario where experimental measurements can be used to constrain Higgs boson theory during the HL-LHC era. All measurements remain dominated by the statistical component of the uncertainty.

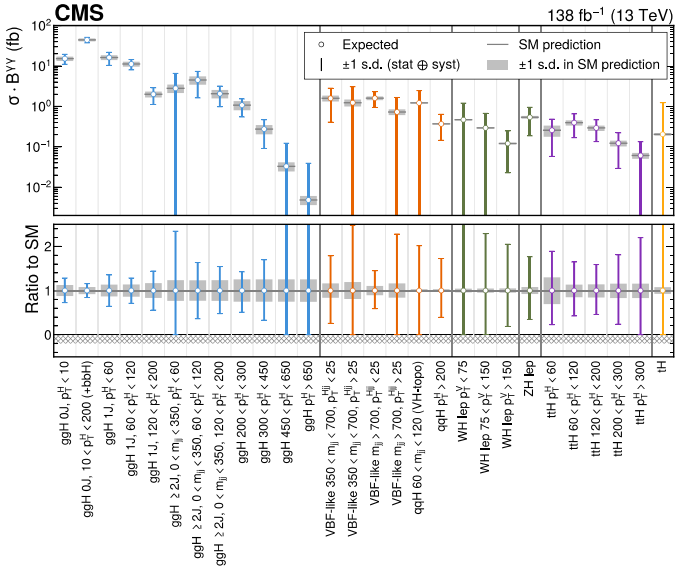

Figure 5: Projected STXS Stage 1.2 Measurements in $H \to \gamma\gamma$ at $L = 3$ ab^{-1} (S2 Scenario). The figure demonstrates the anticipated improvement in precision across various STXS bins. [10]

The projections for $\mathbf{H \to Z\gamma}$ indicate that CMS is expected to achieve independent discovery of this decay channel with a significance of $\mathbf{4.8}\,\sigma$ ($\mathbf{5.8}\,\sigma$) at 2 ab^{-1} (3 ab^{-1}) [10].

6. Summary and outlook

The most comprehensive analysis of Higgs boson properties from the LHC Run 2 data is delivered by the CMS experiment. The combination of numerous decay channels and production modes has yielded the most precise measurements to date of the Higgs boson's couplings, production cross sections, and kinematic distributions. While the vast majority of these measurements show excellent agreement with the Standard Model, a consistent pattern of tension has emerged. In particular, intriguing excesses observed in tH production and in high-transverse-momentum VH production are visible across multiple measurement frameworks – from signal strengths to STXS bins to specific SMEFT coefficients – providing clear and compelling targets for future scrutiny. These precision results establish a critical benchmark for the ongoing LHC Run 3 and the forthcoming High-Luminosity LHC, whose larger datasets will enable even more stringent tests of the Standard Model and deepen the understanding of the electroweak sector.

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